# Teleconnections Associated with Central US Droughts and Floods: Interactions with Sea Surface Temperatures

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## 1. Introduction

In his survey on causes of United States (US) drought, Namias (1983) pointed to empirical evidence for the non-local nature of the phenomenon, particularly during the onset phase. The ensuing drought of 1988 and the flood of 1993 have strengthened this viewpoint that extreme local anomalies in central US rainfall are often manifestations of anomalous atmospheric conditions spanning the Pacific-North American regions. The notion of a "creeping" element to the behavior of drought notwithstanding (Tannehill 1947), the instrumental record offers sufficient examples for rapid development of the meteorological conditions associated with drought (e.g, Namias 1983; Trenberth et al. 1988; Lyon and Dole 1995), and these can only be reconciled with circulation driven processes.

During the development of drought, for example, an upper level anticyclone is typically observed over and just west of the inflicted region, and this is usually linked with upstream circulation anomalies (e.g., Namias 1983; Dole 2000). These wavetrain patterns resemble the teleconnection structures associated with preferred modes of intrinsic atmospheric variability (e.g., Gutzler and Wallace 1981). Similar patterns can also be forced and maintained by sea surface temperature anomalies (e.g., Horel and Wallace 1981), and the question is whether the drought and flood producing teleconnections relevant for central US growing season rainfall may also be forced by air-sea interactions. Observational studies, for example, find significant correlations between North Pacific sea surface temperatures (SSTs) and summertime US rainfall (e.g, Namias 1983, Ting and Wang 1997), though cause and effect has not been resolved. The results of Ting and Wang (1997) also imply an association between tropical Pacific SSTs and Great Plains summertime rainfall during 1950-90, a result found in Bunkers et al. (1996) using the longer 1880-1990 record.

That tropical SSTs may be particularly important factors in contributing to droughts and floods in the central US has been a conclusion drawn from analyses of the springtime 1988 and 1993 events (e.g., Trenberth et al. 1988; Trenberth and Branstator 1992; Trenberth and Guillemot 1996). Each case coincided with an extreme phase of the El Niño/Southern Oscillation (ENSO), with cold event conditions in 1988 and warm event conditions in 1993. Furthermore, each event was accompanied by a similar atmospheric teleconnection pattern (though having opposite polarity), that appeared to originate from the Pacific sector. Trenberth and collaborators proposed that changes in tropical east Pacific rainfall and their associated atmospheric heating initiated planetary-scale circulations that directly contributed to the 1988 drought, and possibly to the 1993 flood.

Dynamical studies on whether teleconnections capable of disrupting central US rainfall can be forced from the tropics have yielded contradictory results. On the one hand, experiments using stationary planetary wave models have yielded wavetrains resembling the 1988 drought circulation pattern when driven by anomalous atmospheric forcing over the tropical east Pacific (e.g., Trenberth et al. 1988; Trenberth and Branstator 1992; Lau and Peng 1992). On the other hand, a Green's function analysis of the springtime climatological flow within a similar model by Liu et al. (1998) shows negligible influence of the equatorial Pacific on North American circulation. From a detailed budget analysis of 1988 and 1993, they argue that the tropical east Pacific rainfall anomalies associated with ENSO played only a minor role, and support the conclusions of others that simple Rossby wave propogation from the tropical east Pacific is not the primary, nor necessarily even an effective, source for drought-producing teleconnections (e.g., Lyon and Dole 1995; Chen and Newman 1998). The possibility exists, however, that the springtime North American circulation may be sensitive to other atmospheric heating anomalies. In particular, the west Pacific is a region identified in the barotropic model experiments of Newman and Sardeshmukh (1998) and Chen and Newman (1998), though the link between rainfall variations there and SST forcing remains to be determined.

The few atmospheric general circulation model (GCM) studies on this problem have failed to clarify the origin of teleconnections related to central US hydrologic extremes in general, and the role of SST forcing in particular. To be sure, some hindcast skill has been reported in 30-60 day experiments focusing on the 1988 drought, but analysis of one set of such runs attributes that skill to the atmopsheric initial conditions rather than SST boundary conditions (Mo et al. 1991), while analysis of another set finds the prescribed soil moisture anomalies to have been more important than the SST anomalies (Atlas et al. 1993). Indeed, Trenberth and Branstator (1992) found climate simulations forced only with global SSTs to be unsuccessful in reprodcuing the atmospheric conditions of 1988, though the reason for failure was argued to stem more from GCM error rather than shortcomings in their empirically-derived hypothesis of drought-producing teleconnections.

There is general agreement that new model experiments are required to establish the role of SSTs in the 1988 and 1993 cases specifically, and to understand the origin of drought and flood producing teleconnections as a whole. Various shortcomings in some of the GCM methods discussed above cast doubt on their robustness. Perhaps most severe has been the small ensembles used, making it difficult to assess the statistical significance of results. It is worth recalling that the model hindcasts of Palmer and Brankovic (1989), often cited as evidence in support of the notion for strong tropical SST forcing during 1988, was based on a single run, and that a second run differing only by one day in atmospheric initial conditions was unskillful. Furthermore, the possibility that biases of any single model can obscure the physical processes responsible for teleconnections suggest the need for both improved models and a multi-model approach. Trenberth and Branstator (1992) discuss attributes which a GCM should possess to be suitable for the problem at hand. Models will of course never be "perfect" and it is unclear how "good" they need to be, nonetheless it will be useful to assess which features, believed to be important in nature, are reproduced in different GCMs.

The current study uses large ensembles of climate simulations forced by the specified global SSTs during 1950-99 to determine the spatial structure of teleconnections related to springtime central US drought and flood, and assess the role of air-sea interactions. Four different GCMs are used in the study, and these as described in section 2 along with details of the experimental design. Each model can be viewed as state-of-the-art in the sense that it is employed in experimental seasonal climate prediction efforts. As a point of comparison with previous studies, the simulations for the 1988 and 1993 events are analyzed in section 3. Our focus then shifts to a broader assessment of the problem by considering the teleconnections associated with springtime US hydrologic extremes throughout the entire half century. A two-fold approach involving parallel analysis of observational and simulated data sets is used. We first inquire into the existance and origin of teleconnections associated with hydrologic extremes, and for this purpose analyze the circulation patterns that are associated with an index of central US rainfall. The GCMs are shown to simulate realistic hydrologic variations in this region, though for some models the teleconnections related to those differ substantially from the observed teleconnection pattern. We next pose the hypothetical question of whether central US rainfall extremes would exist in the GCMs if they generated the precise drought and flood producing circulation patterns found in nature. The GCMs are shown to be capable of producing such teleconnections, though for some models these do not necessarily lead to seasonal rainfall extremes. Under both these scenarios, section 3 assesses the extent to which the observed and simulated teleconnections are related to air-sea interactions and anomalous tropical heat sources. Section 4 gives a discussion and interpretation of the results, and a summary appears in section 5.

The timely delivery of moisture to support crop plants and related agricultural needs is keystone to a successful growing season. Indeed, there is a rich history of scientific effort in the US to explain and anticipate failures in precipitation delivery during the growing season, spurred largely by the devasting 1930's drought. At that time, the intent was to develop a long-lead predictive capacity within the US Weather Bureau that could mitigate the impacts of hydrologic extremes on agriculture and society (Hecht 1983). In this new, proposed project, we seek to understand the origin of warm season US climate variations, and assess the prospects for their predictability. We are interested in investigating what causes the onset of drought, identifying the characteristic teleconnections and their association, if any, with global sea surface boundary conditions. We are also interested to formulate and test new hypotheses on factors controlling warm season climate variability. To this end, we will employ idealized model and GCM simulation data sets to explain empirical relationships occurring in the instrumental record, and assess their predictive capacity.

The rapidity with which drought can develop reflects the importance of circulation driven processes during the initiation phase, though land surface processes can also play a role especially during the maintenance phase of drought (e.g., Namias 1960; Oglesby and Erickson 1989; Lyon and Dole 1995). A recent paradigm for the origin of US drought holds that teleconnection patterns, having a continental anticyclone as their principal center-of-action, can be efficiently forced by the springtime east Pacific SST anomalies associated with ENSO (Trenberth et al. 1988, Trenberth and Branstator 1992). An alternative hypothesis by Chen and Newman (1998) argues that the teleconnections conducive for US drought are most efficiently forced from the subtropical west Pacific. Using a rainfall index centered on the Midwest, Figure 1 (middle, left panel) shows the 500 mb height composite for the 10 driest April-June seasons of the last half century. These composite circulation features, which were particularly well-developed during the 1988 Midwest drought, reveal the non-local nature of the drought phenomenon. They suggest that the continental high, with its induced large-scale subsidence and drying effect, has a Pacific source. The April-June circulation associated with wet Midwest conditions is by-and-large the inverse of its dry counterpart, and once again appreciable circulation anomalies exist upstream of the target region (Fig. 1, middle right panel).

We would like to understand the origin of these teleconnections, especially the extent to which air-sea interactions are involved. Empirical analysis indicates that a characteristic Pacific SST anomaly pattern, with loadings in both the tropics and the midlatitudes, is associated with summer season US precipitation extremes (Namias 1982; Ting and Wang 1997). It is known that the extratropical Pacific SST anomalies are readily forced by the atmosphere, leaving open the question whether their relation with US rainfall is diagnostic or prognostic. On the other hand, equatorial Pacific SSTs have been argued to be imporant factors in the origin of the 1988 drought and 1993 floods (e.g., Trenberth and Guillemot 1996) , however, the statistics of such a causal link are difficult to develop from the brief observational record.

To better understand the teleconnections involved with long-lived US hydrologic extremes, analyses parallel to those performed with observed data can be repeated with GCM data. These take advantage of the ensembles available from the model, and the lower panels of Fig. 1 illustrate the composite teleconnections accompanying the 25 driest and 25 wettest occurences of April-June Midwest rainfall in a 10-member GFDL ensemble that spans 1950-94. The simulations confirm that the circulation patterns related to warm season Midwest rainfall extremes are non-local. Further analysis of these and related GCM runs discussed in section 2 will be used to clarify the influences by air-sea interactions and their potential predictability.

Case studies suggest that different teleconnection patterns are involved with long-lived hydrologic extremes occurring over different portions of the US. Furthermore, the temporal features of dry and wet episodes indicates that these tend to be initiated at preferred times of year (e.g., Diaz 1983), and it is reasonable to suppose that the annual cycle plays an important role. The diversity of the annual cycles of precipitation across the US (Fig. 2) reflects different precipitation sources, including a single July/August monsoonal peak in the Southwest (e.g., Higgins et al. 1997), semiannual peaks in spring and fall in the southern Plains, a mid-summer peak in the central Plains, and a late summer peak in the Southeast. There is some indication that interannual variations are phase-locked with the annual cycle, and Namias (1983) suggested that seasonal forcing may be an important factor favoring an early summer period for the initiation of Great Plains drought. In this regard, it is interesting to note that the evolution of the 1930's northern Plains drought and the 1950's southern Plains drought are distinctively sawtooth in time (Fig. 3), characterized by a recurrent interannual failure of summer rainfall, rather than by a uniform depletion of precipitation during all seasons. Once again, an understanding of the processes responsible for maintaining the annual cycle will be useful for understanding such interannual to decadal variations.

Beyond the problem of long-lived US hydrologic extremes, an ongoing inquiry into the factors controlling US summertime climate variability in general has been driven by several hypotheses. One concerns the effect of global sea surface temperatures, and we have already mentioned the notion that ENSO may have played a role in 1988 and 1993. Using historical station data, Ropelewski and Halpert (1987; 1996) found a wet signal during El Niño over the interior West, but found no evidence for a statistically significant effect elsewhere. More recent studies, using different empirical methods, hint at additional ENSO signals over the central and eastern half of the US during summer (e.g. Livezey et al. 1997; Dole 1999). Montroy et al. (1998) found non-ENSO SST forcing in the west-central and far western tropical Pacific to be associated with significant warm season rainfall anomalies, providing support for the Chen and Newman (1998) hypothesis that the west Pacific warm pool region is an important center of action for US summertime climate variability. Asymmetries in the composites are found when the climate anomalies are calculated for warm and cold SSTs separately, and Montroy et al. find the US anomalies related to their SST modes to be completely nonlinear. Given that such results are derived from short data records, it remains to be confirmed by new dynamical studies or empirical analyses using independent data that these composites, including their linear and nonlinear manifestations, constitute robust and predictable signals.

Alternate hypotheses on factors influencing US continental climate concern the effect of the major summertime monsoons. Higgins et al. (1999) find a relationship between the onset of monsoon rains over southwest Mexico and subsequent seasonal rainfall over all of Mexico and a large portion of the central and northern Plains. Their study rekindles the notion of a north-south dipole in summertime rainfall variability between the Pan American monsoon and the continental US. Once again, which aspects of this relationship are diagnostic versus predictive, and furthermore which aspects of the covariability are related to global SST states, remain open questions.

A theory for the influence of the Asian summertime monsoon on North American climate has recently been proposed by Chen (1999a,b), and is discussed in more detail in section 5. An important conclusion from that study is that convection in the Asian monsoon is largely responsible for the maintenance of the Pan American circulation systems and the neighboring Pacific and Atlantic subtropical highs. The results were derived from an analytic model of the atmosphere forced by idealized heating, and this model can be conveniently manipulated to test the role of the Asian monsoon as a source of global climate variability. For example, the theory predicts an out-of-phase relation between surface pressure variations in the Asian-west Pacific region and those in the North Atlantic. Figure 4, which presents a one-point correlation map of summertime sea level pressure for a base point in the far west Pacific, confirms that this indeed occurs in nature. Whereas the empirical analysis is merely a description, the framework of the simple model offers a physical explanation. It is our wish to use such a simple model to explore other factors that determine the progression of the seasonal cycle of the Pan American circulation systems from spring to summer, especially with regard to the role played by evolutionary aspects of the global monsoons.